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SOME ASPECTS OF FATIGUE CRACK CLOSURE IN TITANIUM ALLOYS.(U)
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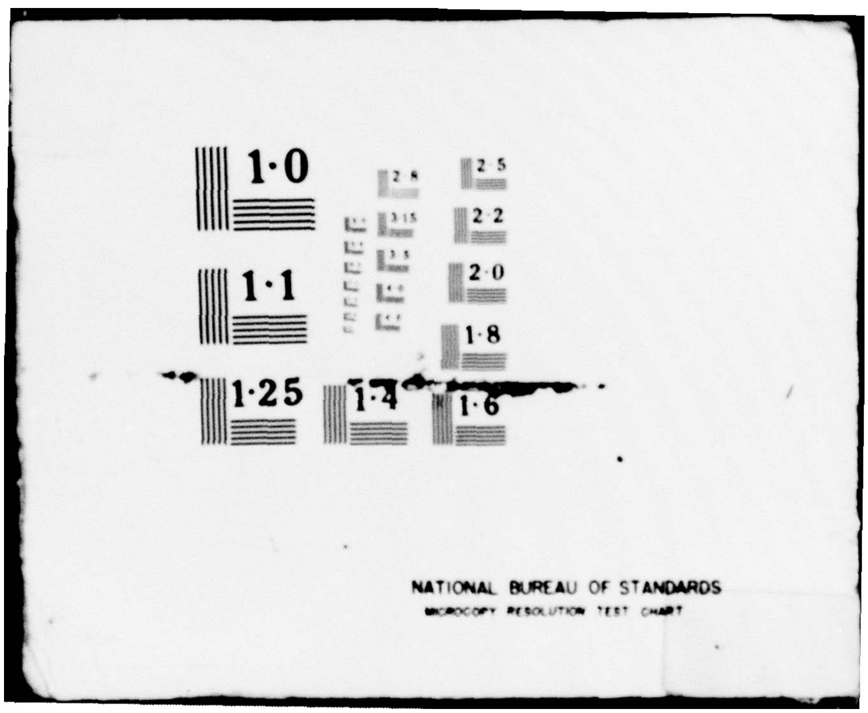
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SOME ASPECTS OF FATIGUE CRACK CLOSURE IN TITANIUM ALLOYS

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20. Abstract

Fatigue crack growth at intermediate rates and R 0.1 has been measured in compact tension specimens of the alloys Ti-6Al-4V and Ti-6Al-5Zr-0.5Mo-0.25Si. Crack length was determined from the output of a crack mouth displacement gauge and by using a d.c. potential drop technique. The incidence of crack closure was examined during fatigue by using both of the above methods; COD was found to be more reliable for closure measurement than potential drop. In contrast to the fine microstructured Ti-6Al-4V, the coarse Ti-6Al-5Zr-0.5Mo-0.25Si showed substantial load transfer across the crack faces during fatigue and this was attributed to a "non-closure" mechanism. Low crack growth rates in the latter alloy were rationalized in terms of an effective ΔK. Marked reductions in growth rate produced by variable amplitude loading of Ti-6Al-4V could not be explained by crack closure.

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Synopsis

Fatigue crack growth at intermediate rates and R 0.1 has been measured in compact tension specimens of the alloys Ti-6Al-4V and Ti-6Al-5Zr-0.5Mo-0.25Si. Crack length was determined from the output of a crack mouth displacement gauge and by using a d.c. potential drop techique. The incidence of crack closure was examined during fatigue by using both of the above methods; COD was found to be more reliable for closure measurement than potential drop. In contrast to the fine microstructured Ti-6Al-4V, the coarse Ti-6Al-5Zr-0.5Mo-0.25Si showed substantial load transfer across the crack faces during fatigue and this was attributed to a "non-closure" mechanism. Low crack growth rates in the latter alloy were rationalized in terms of an effective ΔK. Marked reductions in growth rate produced by variable amplitude loading of Ti-6Al-4V could not be explained by crack closure.

INTRODUCTION

Fatigue crack closure has been widely examined since the original observations of Elber were reported[1,2]. Essentially these observations were that in some circumstances load transfer occurred across the fracture faces during part of the fatigue cycle. It was suggested that this was due to residual plastic deformation left in the wake of the crack. The applied load range, ΔP, was therefore considered to be an inappropriate parameter with which to correlate crack growth rate and some lower, effective load range, ΔP_{eff}, was more appropriate, where

$$\Delta P_{eff} = P_{max} - P_{op} \qquad \ldots\ldots \quad (1)$$

and P_{op} is the load at which the crack is fully open and P_{max} is the maximum load in the fatigue cycle. The practical implications of a closure phenomenon are very attractive in that they may present an additional means of improving fatigue resistance of structural components by suitable material selection.

In order to quantify crack closure effects it is of course necessary to measure P_{op} and this has produced conflicting views on the merits of several experimental methods. The two most widely used have been the DC potential drop system[3-9] which relies upon electrical conduction across the fracture faces at closure, and the detection of specimen compliance changes[1-7,9-11] at closure by monitoring strain or displacement gauge outputs.

The current work is concerned with a comparison of P.D. and displacement gauge observations of fatigue crack closure in Ti-6Al-4V and Ti-6Al-5Zr-0.5Mo-0.25Si alloys and with relating crack growth rate, $\Delta a/\Delta N$, to an effective load range via equation (1) and a modified Paris-Erdogan relationship[12]

$$\Delta a/\Delta N = A \ \Delta K_{eff}^{\ m1} \qquad \ldots\ldots \quad (2)$$

where $\Delta K_{eff} = fn(\Delta P_{eff})$

EXPERIMENTAL

Compact tension specimens of thickness, B, 20mm and with other dimensions in such proportion as to comply with recommended design[13] were machined from Ti-6Al-4V and Ti-6Al-5Zr-0.5Mo-0.25Si alloys. Both alloys were in the as-received condition having received conventional thermo-mechanical treatment.

The Ti-6Al-4V had been mill-annealed, that is, forged at a temperature high in the $\alpha + \beta$ phase field, solution treated for 2hrs at 700°C and air cooled. The microstructure was mainly elongated primary α but contained transformed β and some retained β at the grain boundaries. The mean linear intercept primary α grain size was 6μm ± 3μm in the transverse direction and 16μm ± 9μm in the longitudinal direction.

The Ti-6Al-5Zr-0.5Mo-0.25Si had received a final working in the β phase field, heat treated above the β transus at 1050°C, oil quenched and aged/stress relieved for 24hrs at 550°C. The mean linear intercept prior β grain size was 0.88mm ± 0.38mm; the grains contained colonies which consisted almost entirely of a fine basketweave of Widmanstätten α.

Mechanical testing was performed on a servo-hydraulic Instron Dynamic Testing Instrument which provided the range of loading conditions necessary for pre-cracking from the machined notch and subsequent fatigue crack growth. It also enabled discrete load cycles to be carried out at low frequency for study of crack closure.

The DC potential drop equipment consisted of a stabilized constant current source of 30A from which the current was passed through the specimen at points I and O in figure 1 using 4BA brass bolts separated 12mm (0.3W)

across the crack plane. The P.D. was monitored via a voltage suppression unit and a high gain amplifier by a strip chart recorder during fatigue and by an X-YY recorder for single low frequency load cycles. A calibration was obtained to enable crack length to be related to P.D.; this is shown in graphical form in figure 2 but was represented by a best fit polynomial for crack length computations. A detailed description of the DC potential drop technique has been presented elsewhere[14].

A Boulton Paul Aircraft type F51 miniature displacement transducer was mounted across the top surface of the specimen as shown in figure 3. The output was fed to the X-YY recorder to monitor the specimen compliance during specific low frequency cycles. The displacement gauge output per unit load was calibrated with respect to crack length and is shown in figure 4. This data was described by a best fit polynomial for computational purposes.

The effect of changes in load amplitude at R 0.1 on crack growth rate and crack closure were examined in Ti-6Al-4V. The form of the load amplitude changes is shown in figure 5. A crack was first grown with load range (1) and after the growth had been established for a few millimeters the load amplitude was increased to (2). When $\sim$1mm of growth at the higher amplitude had taken place the load range was reduced to the original value for a few millimeters of growth. Another period of increased amplitude cycling (3) was then performed followed by a return to the original amplitude (1). In region (2) the maximum load was increased by 50.5% compared with region (1) and in region (3) the maximum load was 83.5% higher than in (1). Crack closure was monitored during the above periods of crack growth.

RESULTS and DISCUSSION

Typical data at intermediate growth rates for fatigue of Ti-6Al-5Zr-0.5Mo-0.25Si and Ti-6Al-4V at R 0.1 in air are presented in figures 6 and 7 respectively. It can be seen that of the two alloys the Ti-6Al-4V showed a substantially higher rate of crack growth. When the Paris-Erdogan relationship[12], namely,

$$\Delta a/\Delta N = B \quad \Delta K^{m} \qquad \ldots\ldots \quad (3)$$

was applied to the data of figure 6 the slope m was $\sim$6.5 which is significantly higher than the values of 2-4 generally found for fatigue crack growth at intermediate rates[15]. In contrast, the m value for the Ti-6Al-4V in figure 7 was $\sim$3. Relatively large m values and low growth rates have been reported previously for β heat treated titanium alloys[16, 17].

Records of PD change versus load and COD versus load were made at intervals during the tests to examine the incidence of crack closure. Schematic responses in the presence of closure are shown in figure 8 to facilitate a discussion of the forms of the curves and their analyses. The decrease in slope of the COD curve from A to D is considered to occur due to the increase in specimen compliance on going from a closed to an open crack. Hence over the linear region AB the crack is fully closed with load bearing contact across the crack faces and the specimen responds as if no crack was present. On going from B to C the crack opens and over the linear region CD the crack is fully open. An experimental difficulty in work on closure is in determining the point C when the crack is just fully open; extrapolating DC to lower loads as shown in figure 8 and locating the point of departure of the extrapolation from the original curve is one method. The form of the schematic PD response in figure 8 shows an approximately constant value of PD from F to G when the crack is fully open and when closure occurs the PD falls away over the region GH as the area of electrical contact across the crack faces increases.

Determination of point G is assumed to give a measure of the closure load.

Crack closure was indicated by both the compliance method and the PD during constant load amplitude testing of Ti-6Al-5Zr-0.5Mo-0.25Si at R 0.1 as shown for example in figure 9. The detection of closure by the P.D. was eratic and the first three P.D. traces in figure 9 do not give a clear indication of the closure load, which was revealed by the COD traces to be a substantial fraction of the maximum applied load. There was also a tendency for the P.D. output to show a higher value of closure load than the COD readings and this is examplified in figure 10. Figure 10 also shows an interesting effect of a decrease in P.D. at the high load end of the cycle. This behaviour has been referred to previously when it was considered to indicate closure at peak load [18]. It was noticeable in the present work that the effect gradually developed at the higher K_{max} values and was probably associated with surface plastic zone size.

The extent of closure during constant load amplitude cycling in the Ti-6Al-4V was small compared with the Ti-6Al-5Zr-0.5Mo-0.25Si and was only found at the high end of the K range used, $\gtrsim 36 MNm^{-3/2}$. (Figure 11). In the example shown in figure 11 closure was detected by the COD gauge only near the bottom of the load cycle but the PD indicated a much higher closure load, confirming the results from the Ti-6Al-5Zr-0.5Mo-0.25Si. Closure was detected by both COD and PD at lower K levels in the Ti-6Al-4V if the specimen was unloaded

The important feature of crack closure is the transfer of load across the fracture faces at some load above the minimum in the fatigue cycle. The above results support the view that the COD method is more successful than the PD method in recording this event. PD measurements of closure were shown to be eratic and this is probably due to variable oxide insulation on the fracture surfaces. Similarly, the tendency for closure levels measured by PD to be higher than from COD traces probably arises from electrical contact

across the fracture faces without significant load transfer[9].

Closure loads were obtained from COD traces for the Ti-6Al-5Zr-0.5Mo-0.25Si test at R 0.1 in the manner indicated in figure 8. Using these values, measures of the effective ΔK at the crack tip were calculated from equations (1) and (2). The crack growth rate data of figure 6 was then replotted in terms of ΔK_{eff} and is shown in figure 12. The slope of the curve, ml in equation 2, is ~ 3 and the growth rates are very similar to those in figure 7 for the Ti-6Al-4V. It would appear that the large differences in growth rate between the two alloys can be rationalized using the ΔK_{eff} approach.

By anology to previous work on large-grained titanium alloy[17], the relatively high levels of load transfer across the fracture faces in the Ti-6Al-5Zr-0.5Mo-0.25Si are assumed to arise because of mismatch of the coarse fracture faces. They are thus prevented from closing and this mechanism has been termed "non-closure"[17] to distinguish it from the plastic wake mechanism of closure[1,2].

As mentioned previously, closure was not detected in the Ti-6Al-4V during constant amplitude loading at R 0.1 except at high K levels, but it was encountered on reducing the load below the minimum in the cycle. This latter behaviour was examined more closely by carrying out a variable amplitude test as described in the experimental section. On increasing the load amplitude, whilst keeping R 0.1, there was an immediate increase in growth rate as measured by the PD without an observed transition region. (Figures 13 and 14, point A). On reducing the load amplitude, the growth rate showed an immediate marked decrease. There was however a transition region (points B in figures 13 and 14) during which the growth rate initially decelerated over a small crack increment to a minimum value and then accelerated until it was out of the zone of influence of the previous, higher amplitude loading. The decrease in growth rate and the extent of the zone of influence of the previous higher amplitude loading were greater for the larger reduction in load amplitude. Closure was examined before and after the decreases in load

amplitude but was not detected by COD. (Figure 15). The PD indicated some closure immediately after a decrease in load amplitude but this only lasted for a few cycles. (Figure 15). Hence the marked decrease in growth rate obtained on decreasing the load amplitude could not be explained by crack closure. This confirms observations of other workers on aluminium alloy[19] and it is likely that the reduced growth rates are associated with residual compressive stresses in the crack tip plastic zone[20].

CONCLUSIONS

1) For the alloys and growth conditions used, the PD method was unsuccessful in measuring crack closure. This was probably due to variable electrical contact across the crack faces because of oxide insulation effect and to an inability of the method to discriminate between rubbing contact and load-bearing contact.

2) The COD method was more reliable in detecting crack closure.

3) The coarse-structured Ti-6Al-5Zr-0.5Mo-0.25Si alloy showed substantial load transfer across the crack faces during constant amplitude load cycling at R 0.1. This was in contrast to Ti-6Al-4V which showed a small amount of load transfer and only at high K levels.

4) Low fatigue crack growth rates in Ti-6Al-5Zr-0.5Si-0.25Mo were rationalized by using an effective ΔK concept.

5) Marked reductions in growth rate resulting from reduced amplitude loading in Ti-6Al-4V could not be explained by crack closure.

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REFERENCES

1. W. Elber, Eng. Frac. Mech., 2 (1970) 37.
2. W. Elber, ASTM STP 386, (1971) 230.
3. T.T. Shih and R.P. Wei, Eng. Frac. Mech., 6 (1974) 19.
4. C.K. Clarke and G.C. Cassatt, ibid, 9 (1977) 675.
5. T.C. Lindley and C.E. Richards, Mat. Sci. Eng., 14 (1974) 281.
6. P.E. Irving, J.L. Robinson and C.J. Beevers, Eng. Frac. Mech., 7 (1975) 619.
7. C. Robin, S. Dominiak and G. Pluvinage, Mat. Sci. Eng., 29 (1977) 145.
8. P.E. Irving, J.L. Robinson and C.J. Beevers, Int. J. of Fracture, 11 (1975) 1055.
9. V. Bachmann and D. Munz, Eng. Frac. Mech., 11 (1979) 61.
10. V. Bachmann and D. Munz, Int. J. of Fracture, 11 (1975) 713.
11. J.D. Frandsen, R.V. Inman and O. Buck, ibid, 11 (1975) 345.
12. P.C. Paris and F. Erdogan, Trans. ASME., 85 (1963) 528.
13. ASTM, Standard E 399 (1972).
14. M.D. Halliday and C.J. Beevers, "The DC Electrical Potential Method for Crack Length Measurement", Measurement of Crack Length and Shape During Fracture and Fatigue, to be published.
15. P.E. Irving and L.N. McCartney, Metal Science J., 11 (1977) 351.
16. G.R. Yoder, L.A. Cooley and T.W. Crooker, Eng. Frac. Mech., 11 (1979) 805.
17. M.D. Halliday and C.J. Beevers, Int. J. of Fracture, 15 (1979) R27.
18. P.E. Irving, J.L. Robinson and C.J. Beevers, ibid 9 (1973) 105.
19. G.R. Chanani and B.J. Mays, Eng. Frac. Mech., 9 (1977) 65.
20. S.G. Druce, C.J. Beevers and E.F. Walker, ibid 11 (1979) 385.

Figure 1

Compact tension specimen geometry showing current input, I, and output, O, positions and potential probe positions, P.

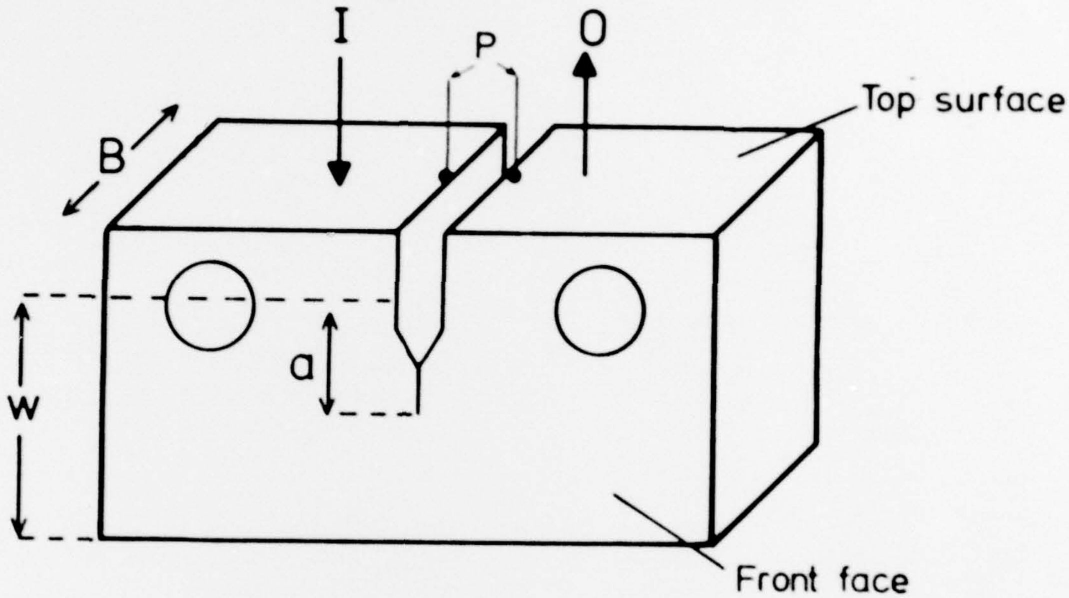
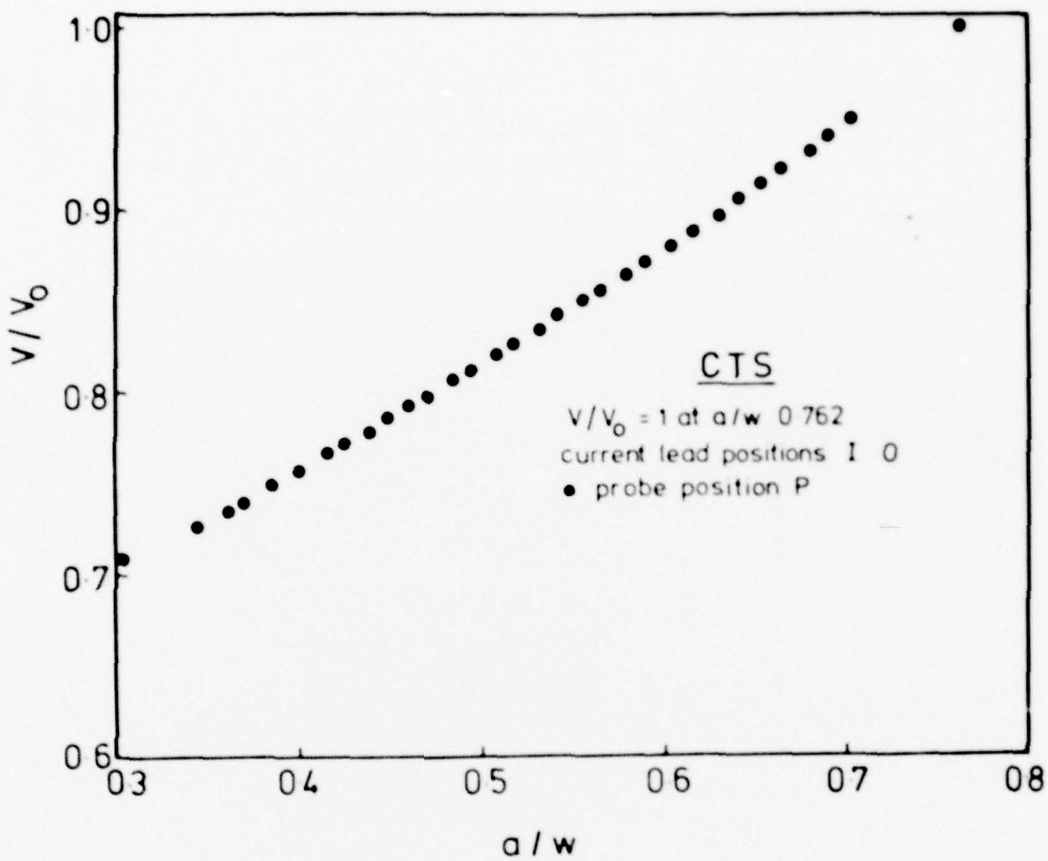

I
P
O
Top surface
B
a
w
Front face

Figure 2

Calibration curve of potential drop ratio (V/V_o) versus crack length ratio (a/W) for a compact tension specimen with the lead attachment points shown in figure 1.



1·0
0·9
0·8
0·7
0·6
V / V_0
CTS
V/V_0 = 1 at a/w 0.762
current lead positions I O
• probe position P
0·3
0·4
0·5
0·6
0·7
0·8
a / w

Figure 3

Compact tension specimen with displacement transducer and potential drop leads attached to the top surface.

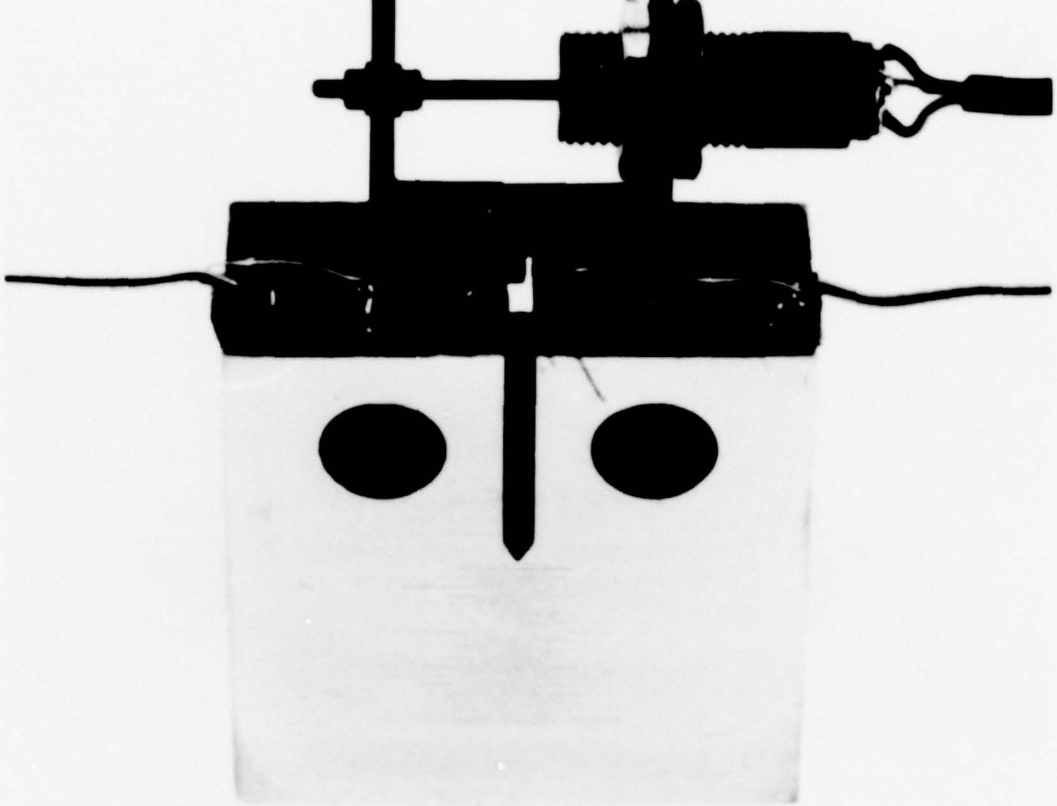
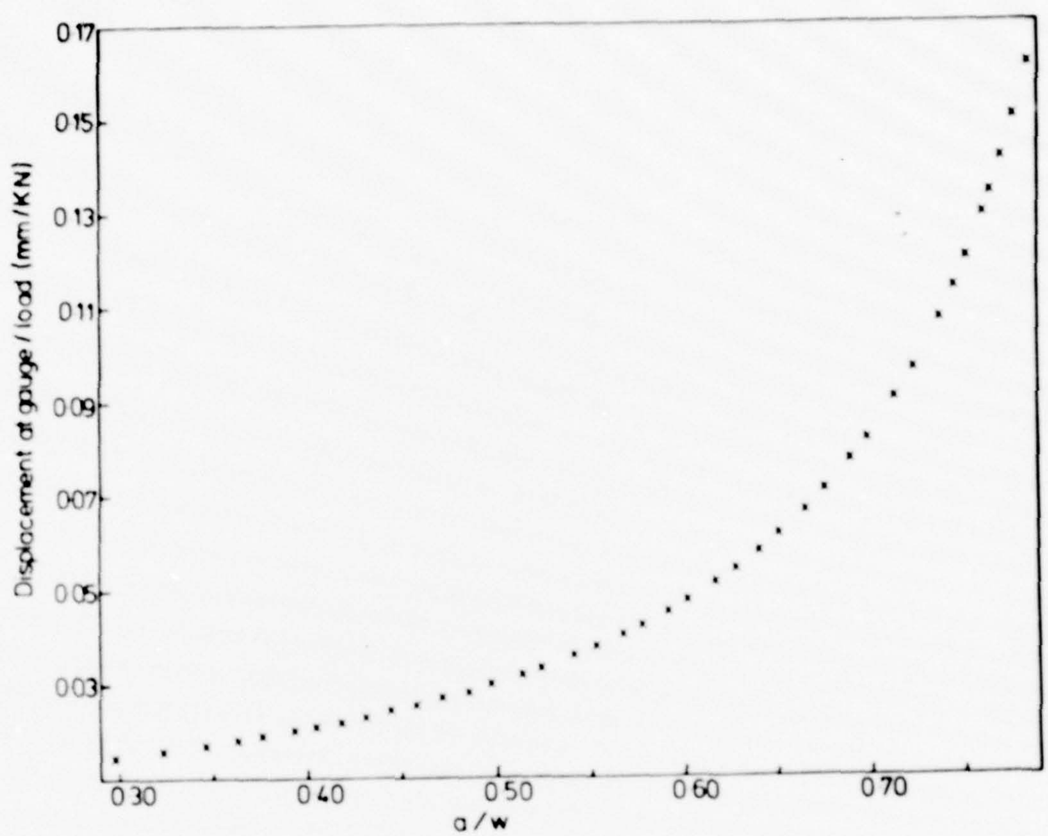


Figure 4

Calibration curve of displacement gauge output per unit load versus crack length ratio (a/W) for a compact tension specimen.



Displacement at gauge / load (mm/KN)
0.17
0.15
0.13
0.11
0.09
0.07
0.05
0.03
0.30
0.40
0.50
0.60
0.70
a / w

Figure 5

Schematic of the load amplitude changes used during crack growth of a Ti-6Al-4V specimen at R 0.1.

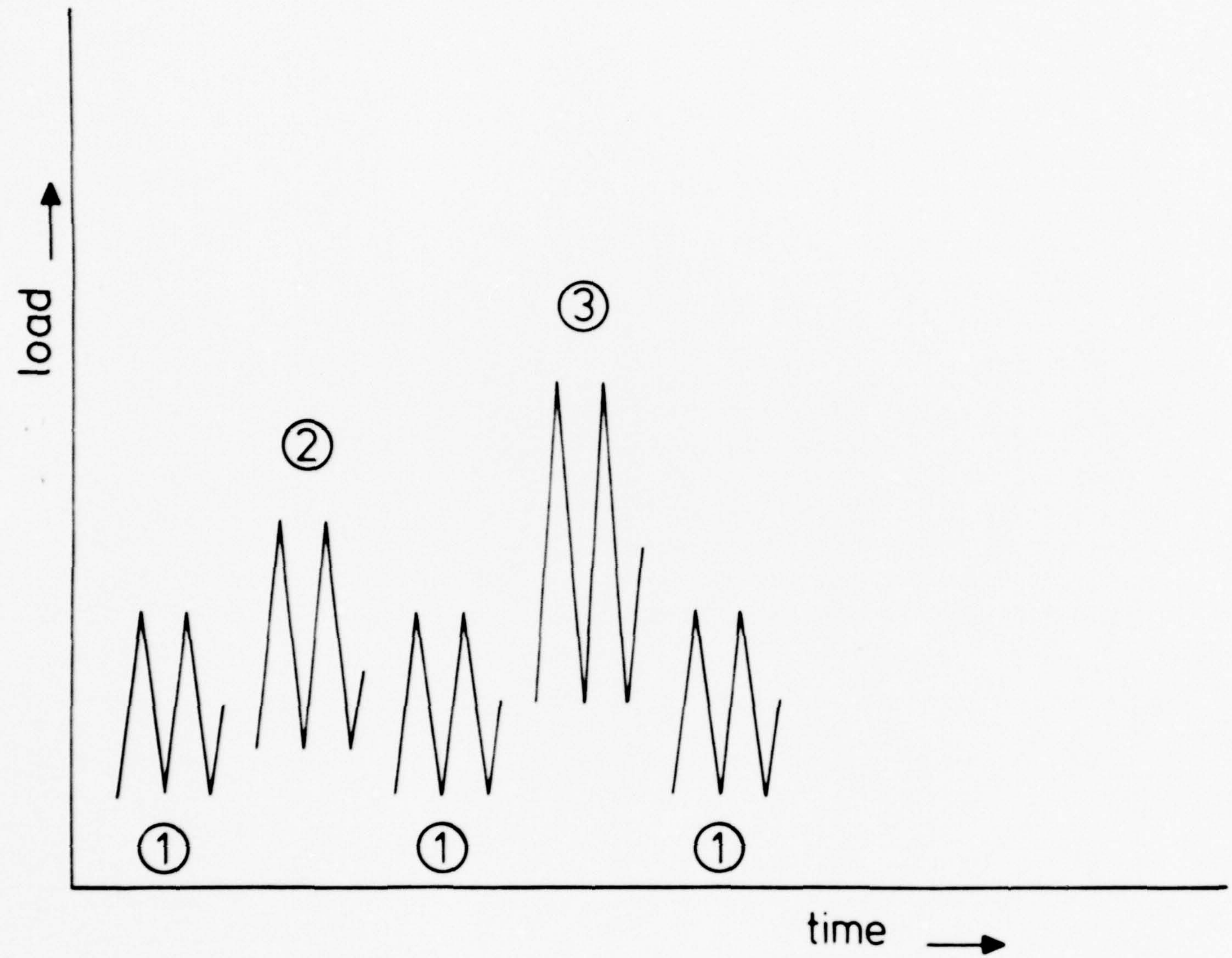

load
time
1
2
1
3
1

Figure 6

Fatigue crack growth data for the Ti-6Al-5Zr-0.5Mo-0.25Si at R 0.1, 8 Hz, laboratory air.

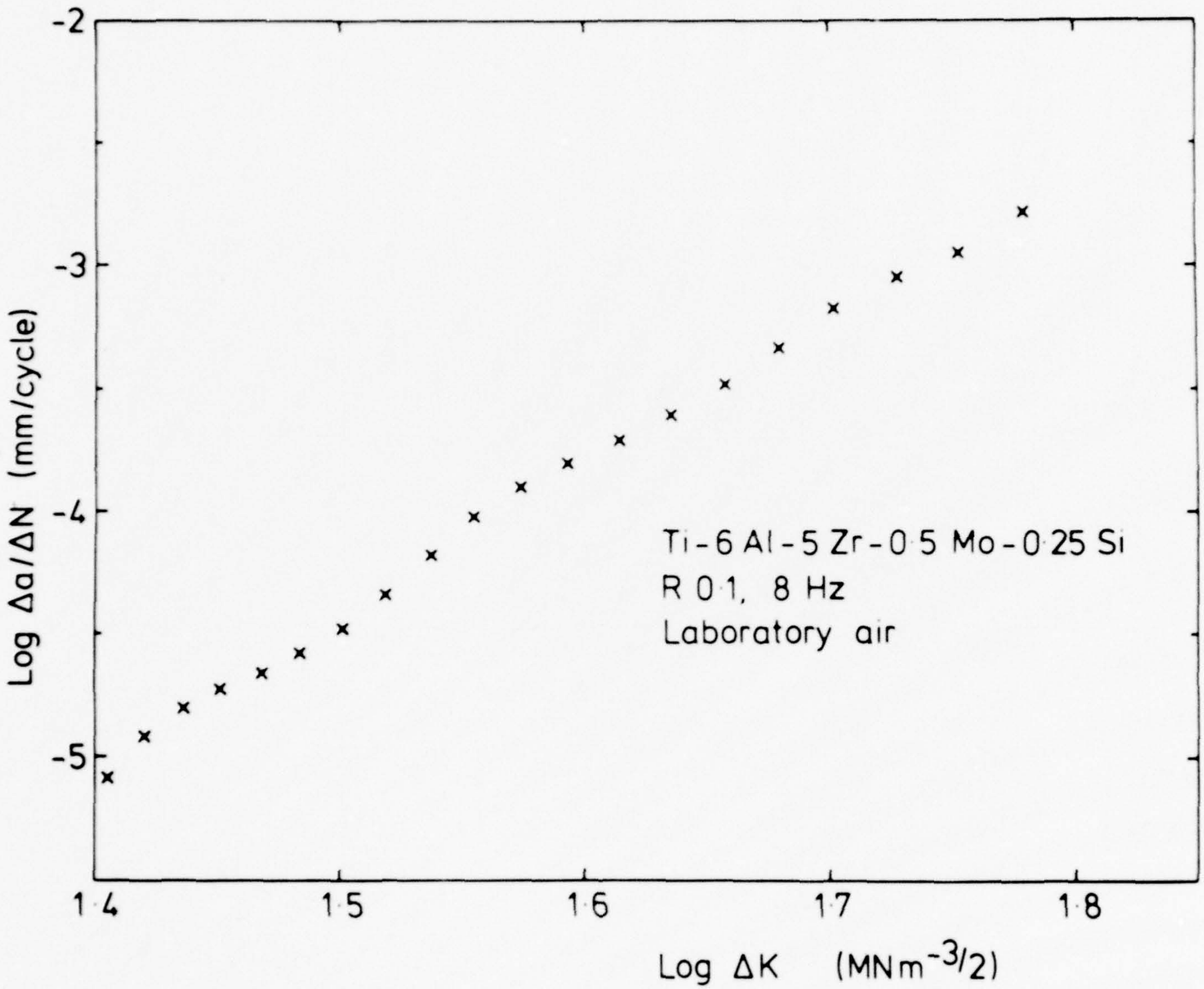
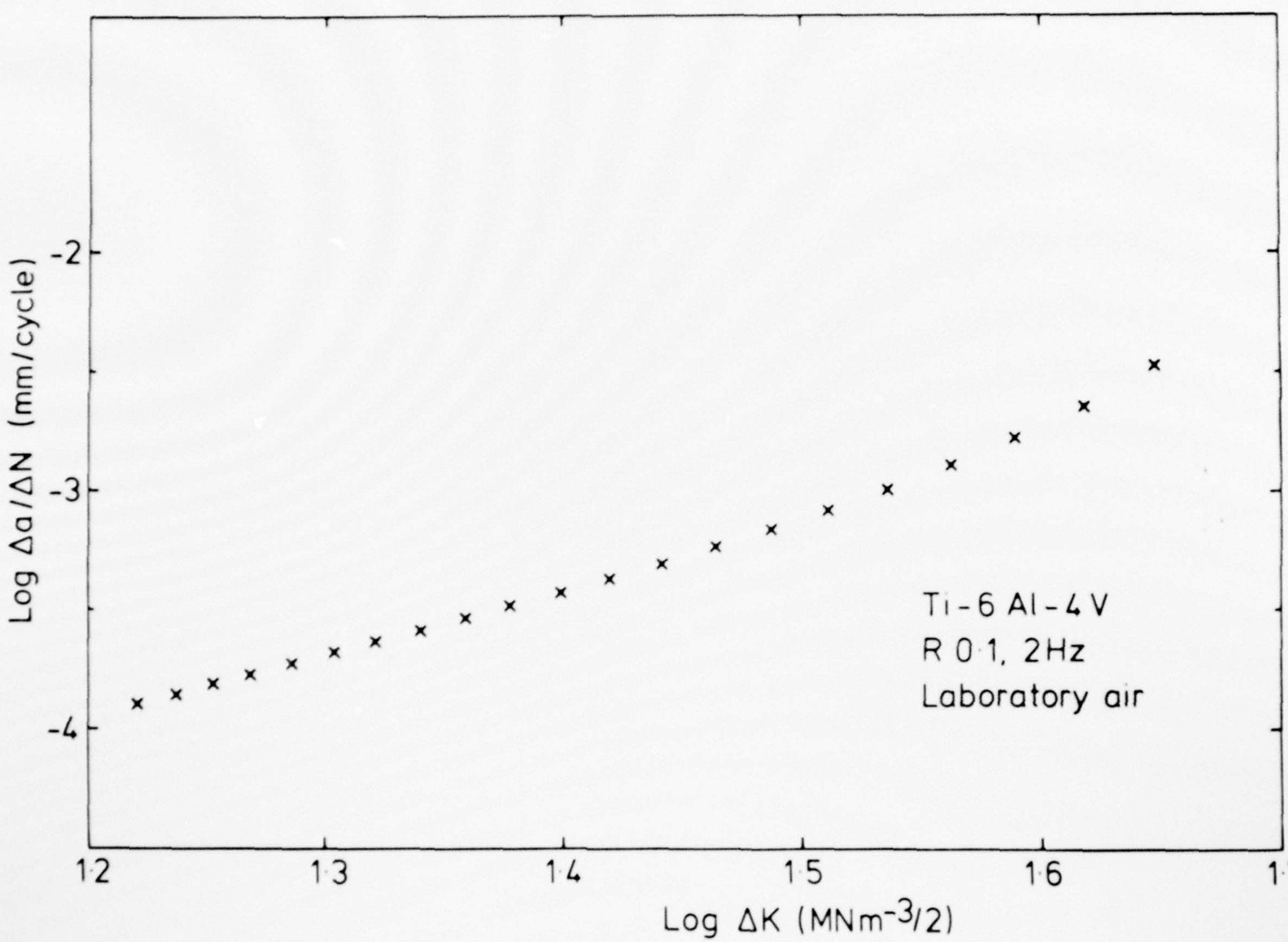

-2
-3
-4
-5
Log Δa/ΔN (mm/cycle)
1·4
1·5
1·6
1·7
1·8
Log ΔK (MNm^-3/2)
Ti-6 Al-5 Zr-0·5 Mo-0·25 Si
R 0·1, 8 Hz
Laboratory air

Figure 7

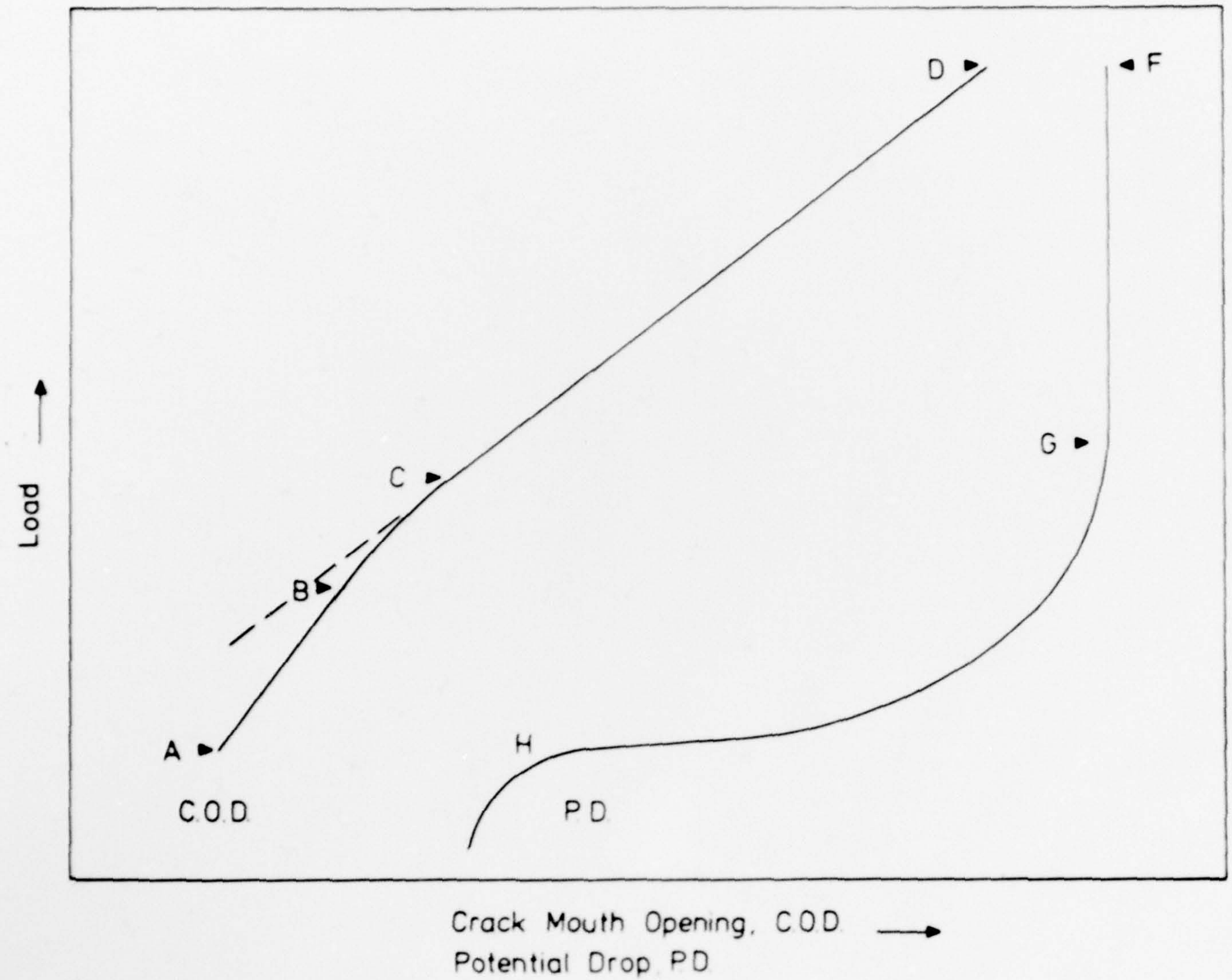
Fatigue crack growth data for the Ti-6Al-4V at R 0.1, 2 Hz, laboratory air.



Log Δa/ΔN (mm/cycle)
-2
-3
-4
1·2
1·3
1·4
1·5
1·6
1·7
Log ΔK (MNm-3/2)
Ti-6 Al-4 V
R 0·1, 2Hz
Laboratory air

Figure 8

Schematic load/potential drop and load/COD curves in the presence of crack closure.



Load
D
F
G
C
B
A
H
C.O.D.
P.D.
Crack Mouth Opening, C.O.D.
Potential Drop, P.D.

Figure 9

Load/COD and load/PD traces recorded during crack growth in the Ti-6Al-5Zr-0.5Mo-0.25Si. The COD traces are consistent in indicating crack closure whilst the PD traces are not.

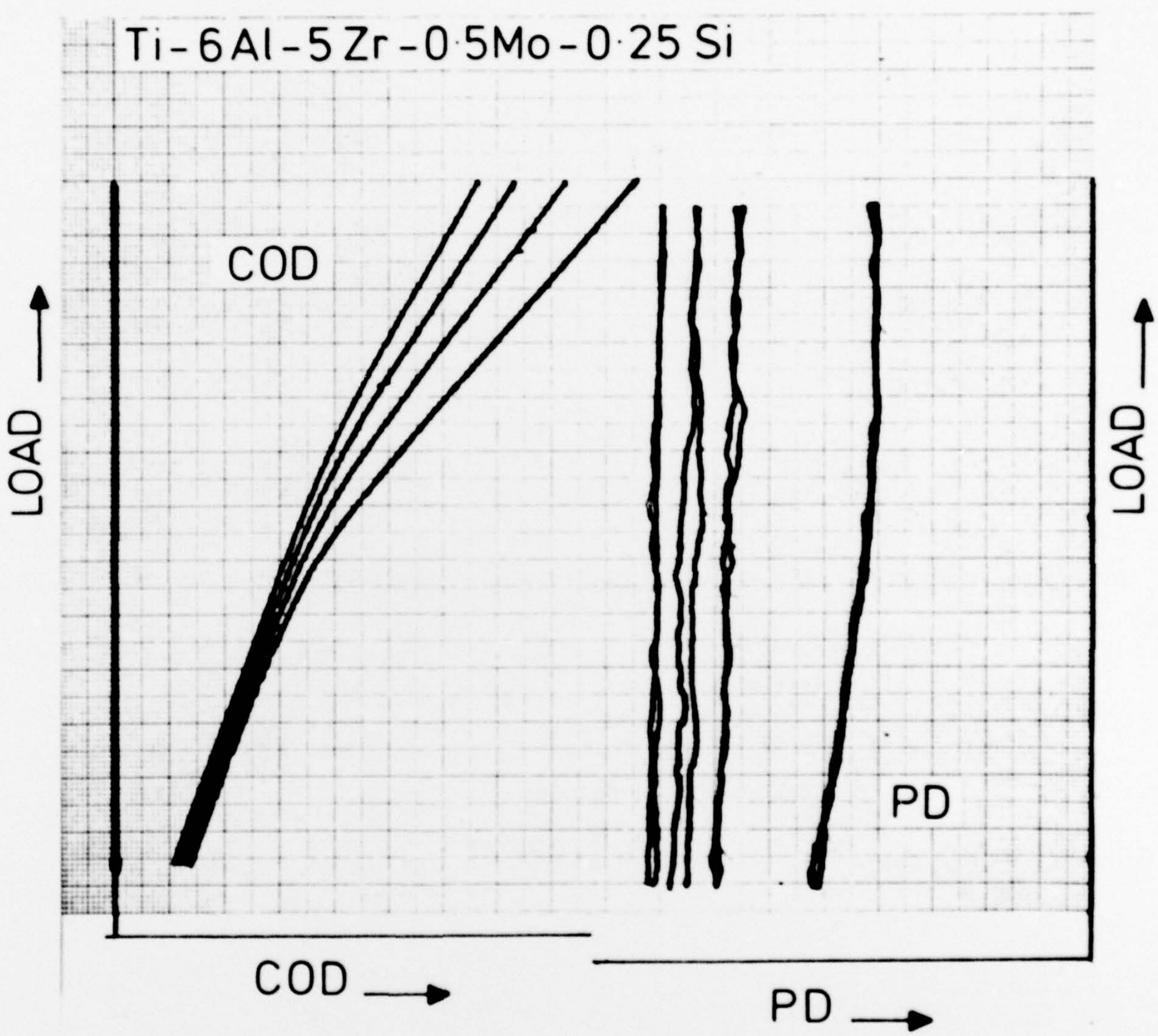

Ti-6Al-5Zr-0·5Mo-0·25Si
COD
PD
LOAD
LOAD
COD
PD

Figure 10

A pair of load/COD and load/PD traces recorded during fatigue of the Ti-6Al-5Zr-0.5Mo-0.25Si. The PD indicates a substantially higher closure load than the COD.

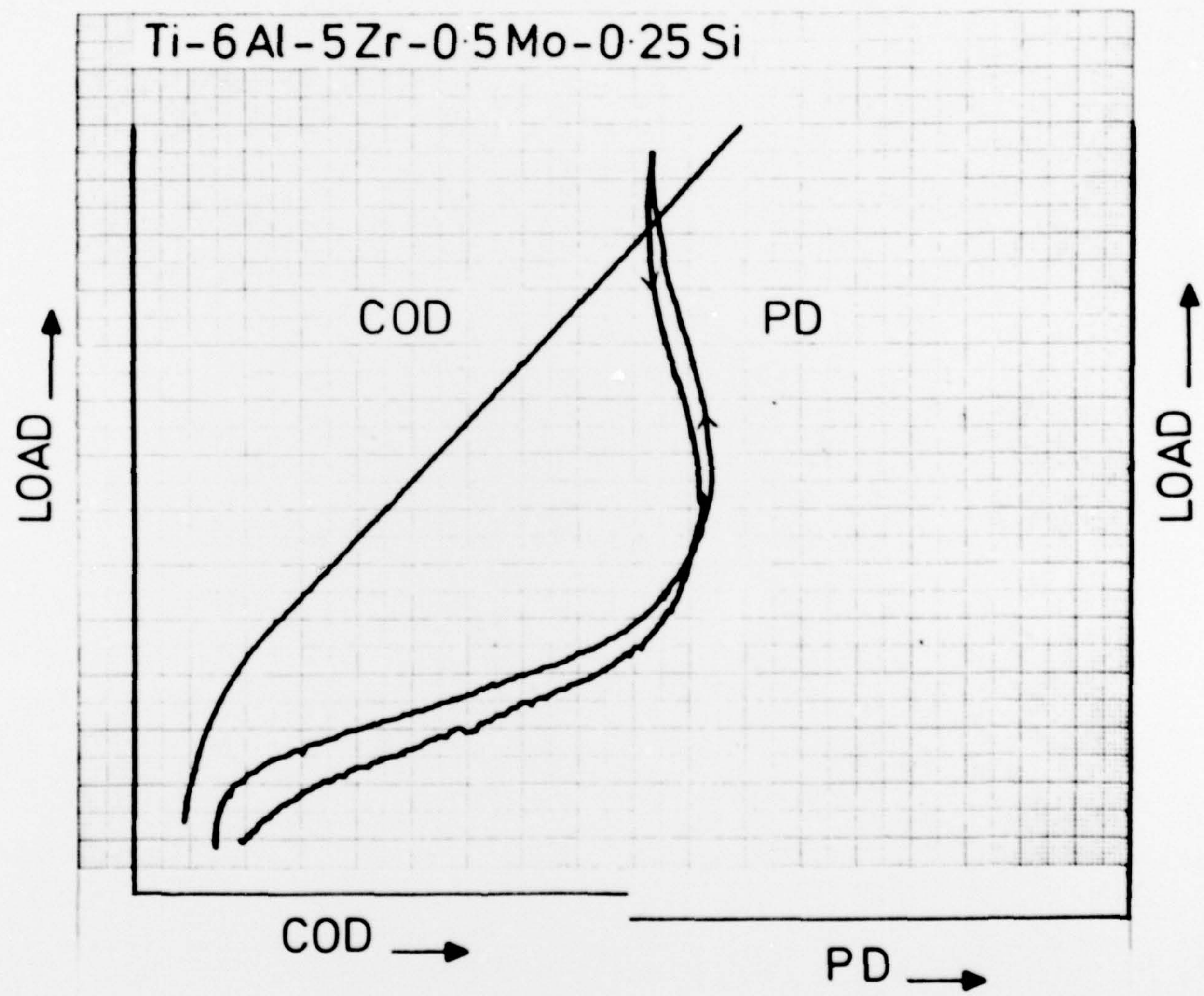
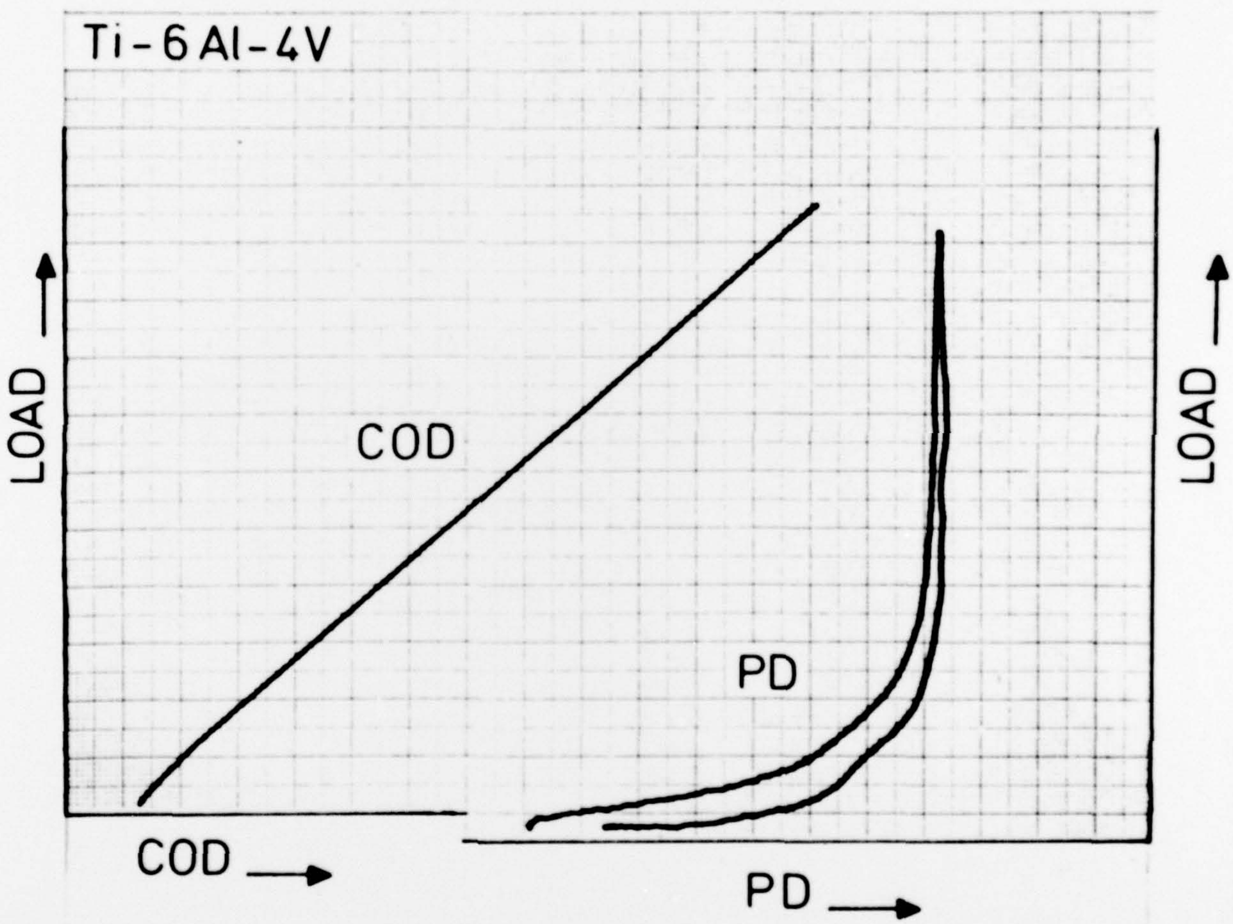

Ti-6Al-5Zr-0·5Mo-0·25Si
COD
PD
LOAD
LOAD
COD
PD

Figure 11

A pair of load/COD and load/PD traces recorded during crack growth in the Ti-6Al-4V. The amount of closure indicated by the COD is much smaller than in the Ti-6Al-5Zr-0.5Mo-0.25Si. The PD suggests a higher value of closure load than the COD.



Ti-6Al-4V
LOAD
COD
PD
COD
PD
LOAD

Figure 12

Fatigue crack growth data of figure 6 for the Ti-6Al-5Zr-0.5Mo-0.25Si re-interpreted in terms of effective ΔK.

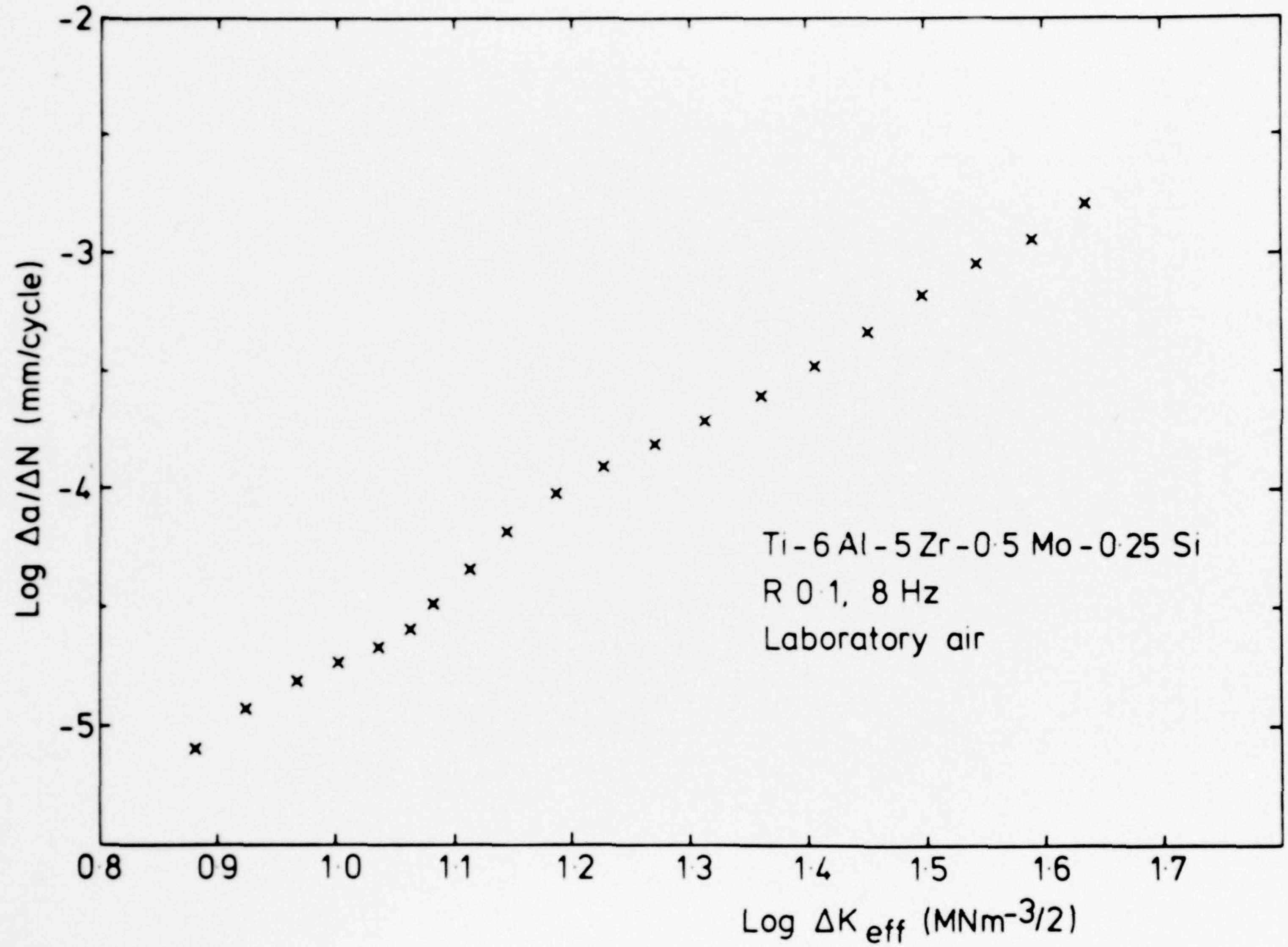
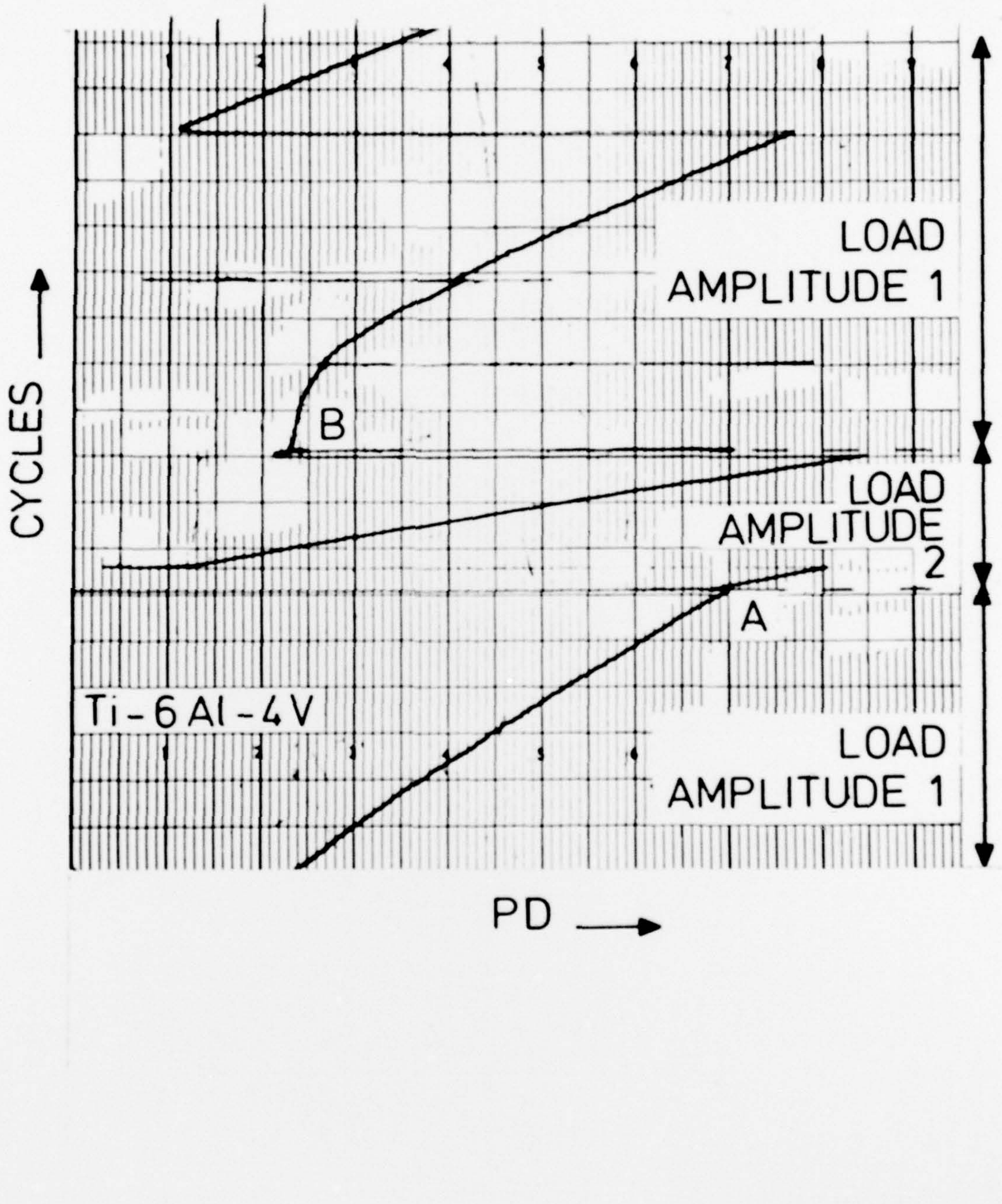

-2
-3
-4
-5
Log Δa/ΔN (mm/cycle)
0·8
0·9
1·0
1·1
1·2
1·3
1·4
1·5
1·6
1·7
Log ΔK eff (MNm-3/2)
Ti-6 Al-5 Zr-0·5 Mo-0·25 Si
R 0·1, 8 Hz
Laboratory air

Figure 13

PD/cycles output for the Ti-6Al-4V during the load amplitude changes 1 → 2 → 1 shown in figure 5. The slopes of the curves at points A and B indicate the nature of the transition in crack growth rate for the particular load amplitude change.



CYCLES
LOAD AMPLITUDE 1
B
LOAD AMPLITUDE 2
A
Ti-6Al-4V
LOAD AMPLITUDE 1
PD

Figure 14

Similar to figure 13 except that the load amplitude change is $1 \rightarrow 3 \rightarrow 1$.

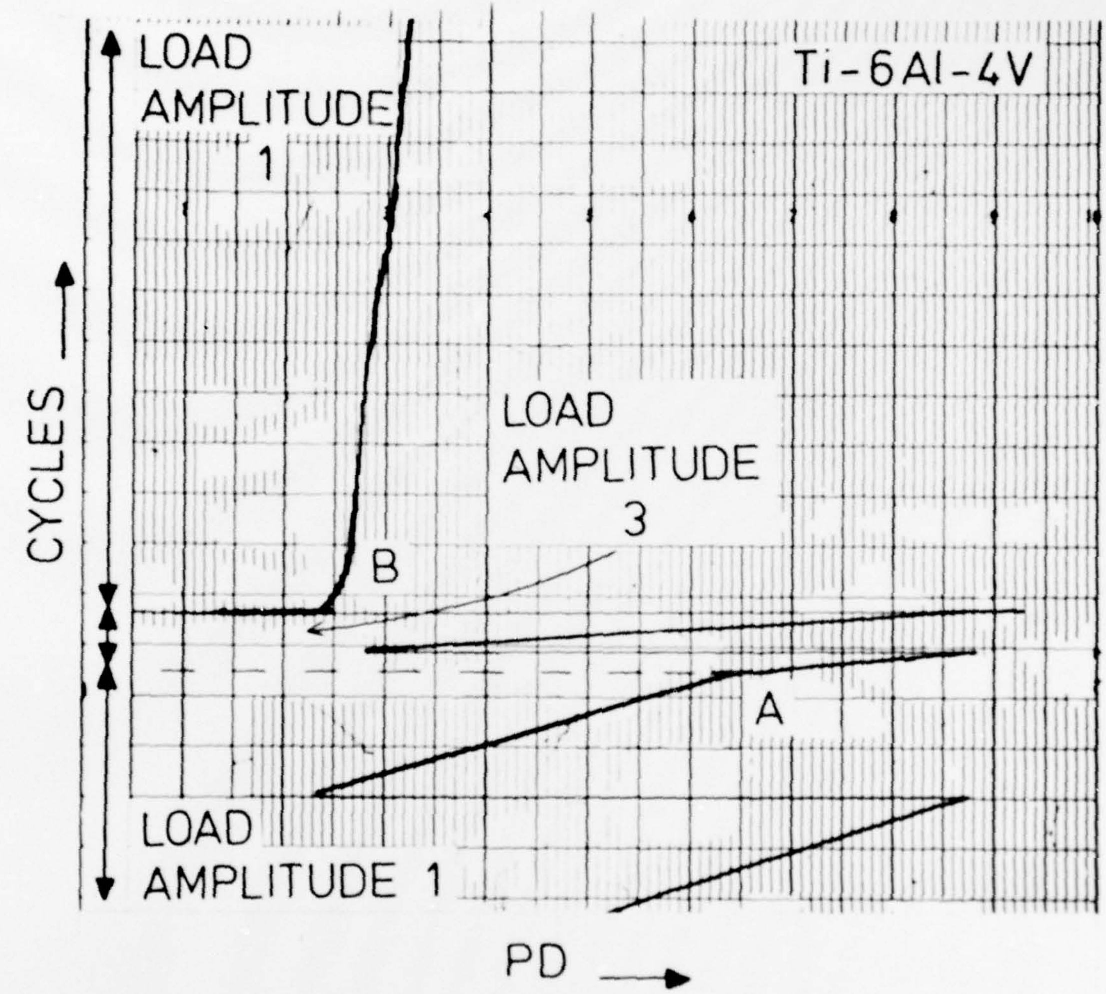
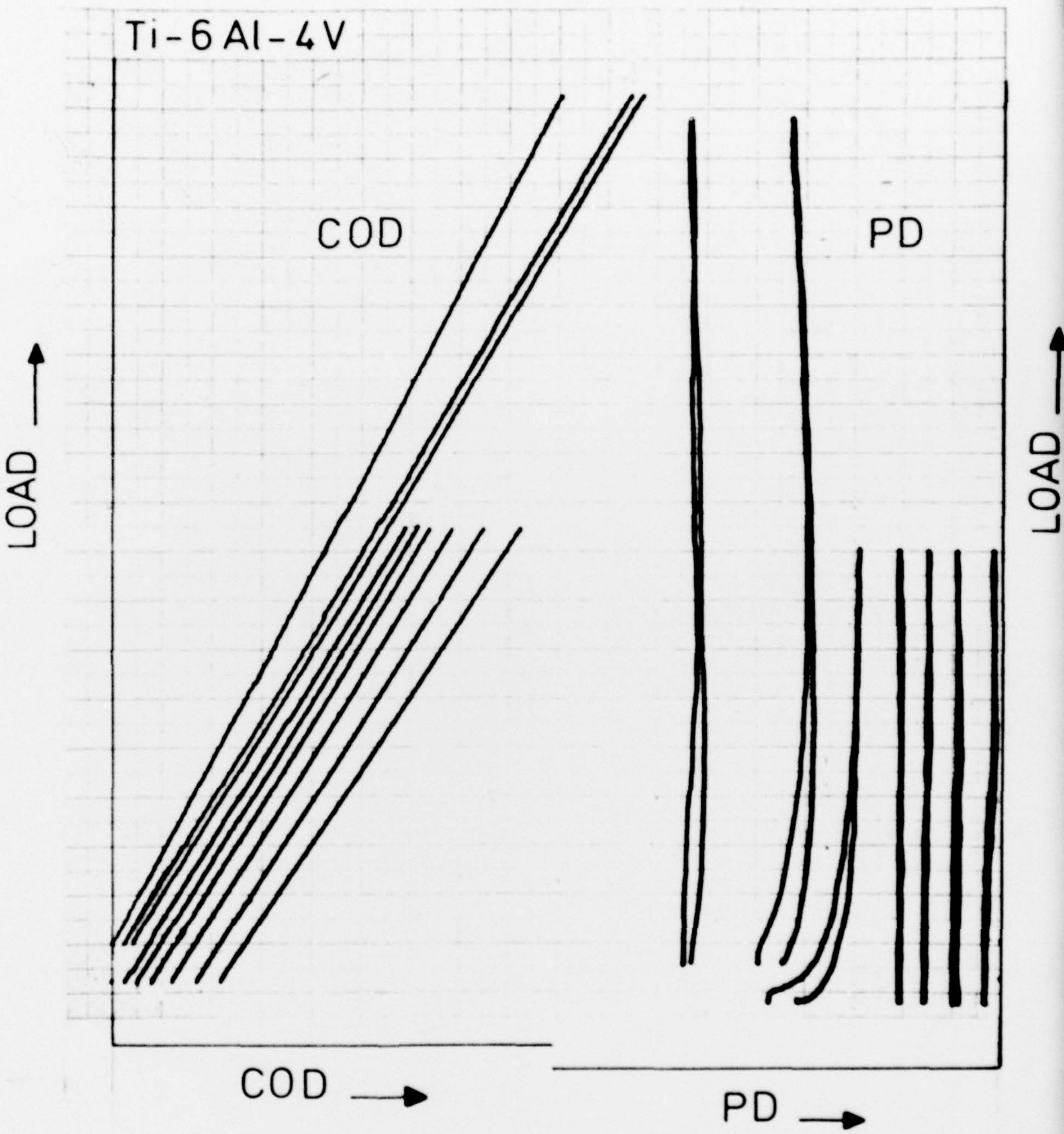

LOAD
AMPLITUDE
1
Ti-6Al-4V
CYCLES
LOAD
AMPLITUDE
3
B
A
LOAD
AMPLITUDE 1
PD

Figure 15

Load/COD traces for the Ti-6Al-4V do not indicate crack closure upon reducing the load amplitude; PD shows closure but it ceased to do so only a few cycles after the load decrease.


Ti-6Al-4V
COD
PD
LOAD
LOAD
COD
PD